

On the nature and detectability of Type Ib/c supernova progenitors

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Received: / Accepted:

ABSTRACT

Context. The progenitors of many Type II supernovae have been observationally identified but the search for Type Ibc supernova (SN Ibc) progenitors has thus far been unsuccessful, despite the expectation that they are luminous Wolf-Rayet (WR) stars.

Aims. We investigate how the evolution of massive helium stars affects their visual appearances, and discuss the implications for the detectability of SN Ibc progenitors.

Methods. Evolutionary models of massive helium stars are analysed and their properties compared to Galactic WR stars.

Results. Massive WR stars that rapidly lose their helium envelopes through stellar-wind mass-loss end their lives when their effective temperatures – related to their hydrostatic surfaces – exceed about 150kK. At their pre-supernova stage, their surface properties resemble those of hot Galactic WR stars of WO sub-type. These are visually faint with narrow-band visual magnitudes $M_v = -1.5 \dots -2.5$, despite their high bolometric luminosities ($\log L/L_\odot = 5.6 \dots 5.7$), compared to the bulk of Galactic WR stars ($M_v < -4$). In contrast, relatively low-mass helium stars that retain a thick helium envelope appear fairly bright in optical bands, depending on the final masses and the history of the envelope expansion during the late evolutionary stages.

Conclusions. We conclude that SNe Ibc observations have so far not provided strong constraints on progenitor bolometric luminosities and masses, even with the deepest searches. We also argue that Ic progenitors are more challenging to identify than Ib progenitors in any optical images.

Key words. Stars: evolution – Stars: Wolf-Rayet – Stars: binary – supernovae: general

1. Introduction

Direct detections of the progenitor stars of supernovae discovered in the nearby Universe provide one of the most stringent constraints on stellar evolution theory. Since the unambiguous identification of the progenitor of the supernova 1987A, observers have identified progenitor stars of numerous Type IIP supernovae and several Type IIb and IIc supernovae in pre-supernova images (see Smartt 2009, for a review). However, despite their relevance to Galactic chemical evolution, the progenitor stars of supernovae (SNe) Ibc remain as yet elusive.

For decades, there had been a widely held belief that SNe Ibc progenitors are massive Wolf-Rayet (WR) stars, formed either through stellar-wind mass-loss or Roche-lobe overflow in a binary system. Also the identification of broad SN Ic features in the vicinity of several long GRBs (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003) for which the progenitors were also suggested to be massive WR stars (Woosley 1993) added further evidence to this assertion. An alternative to the massive WR scenario is that of lower mass binaries (e.g. Podsiadlowski et al. 1992; Wellstein & Langer 1999; Eldridge et al. 2008; Yoon et al. 2010).

Although many previous searches for SNe Ibc progenitors were hampered by insufficient detection limits, WR stars with $\log L/L_\odot \gtrsim 5.3$ could have been identified as the progenitors of the Type Ib supernova 2000ds (Maund & Smartt 2005), and the Type Ic supernovae 2004gt (Maund et al. 2005) and 2002ap (Crockett et al. 2007). On the other hand, the most recent stellar evolution models predict that WR stars originating from massive single stars with initial masses higher than about $30 M_\odot$ have bolometric luminosities of $\log L/L_\odot \gtrsim 5.4$ at the pre-

supernova stage (Meynet & Maeder 2003; Crockett et al. 2007; Georgy et al. 2012). New detection limits, e.g., on SNe 2002ap, have mostly been interpreted as evidence against the massive WR scenario, but in favour of progenitors of lower mass binaries instead and largely dismissing the option of massive WR stars (e.g., Crockett et al. 2007; Smartt 2009; Yoon et al. 2010).

However, in these interpretations the crucial final stages of massive-star evolution are not properly accounted for, as we argue in the following. In this paper, we present the seemingly counter-intuitive idea that the more massive – and bolometrically more luminous – single WR progenitors are more challenging to detect than low-mass binaries.

2. Massive Wolf-Rayet stars: Models and observations

One of the most crucial questions regarding the observational identification of massive WR stars as SN Ibc progenitors is this: which bolometric correction (BC) should be applied to WR stars at the pre-supernova stage? Because the optical luminosities of WR stars are critically affected by optically thick WR winds, the simple assumption of black-body radiation should not be applied even for a crude approximation (cf. Crowther 2007).

Maund & Smartt (2005) and Maund et al. (2005) calculated BCs for WR stars using the Potsdam grid of synthetic WR spectra (Hamann & Gräfener 2004; Gräfener et al. 2002) and obtained the detection limits for different SNe Ibc progenitors in terms of bolometric luminosities. These detection limits were then compared to the evolutionary tracks of massive stars given by Meynet et al. (1994) to constrain the SN Ibc progeni-

tor masses. The caveat here is that Meynet et al. (1994) applied a correction to the radii of their WR star models to take into account the radial extension of the star due to an optically thick wind, following Langer (1989) and Maeder (1990). This correction is particularly large as they employed high WR mass-loss rates for which the effect of wind clumping was not considered (cf. Hamann & Koesterke 1998). As a consequence, the evolutionary tracks of their WR star models have surface temperatures of $\log T \simeq 4.8$, and Maund et al. applied their BCs accordingly only up to the quoted value. However, the stellar temperatures T_\star of the Potsdam models do not refer to the values at the photosphere within the extended optically thick wind, but to those at large optical depths close to the hydrostatic stellar surface. This inconsistency introduced a large underestimate of the BCs applied to WR stars at the pre-supernova stage, because stellar evolution models predict that massive WR stars with masses $M \gtrsim 10 M_\odot$ end their lives with hydrostatic surface temperatures well above $\log T_\star = 5.0$ (see discussion below). On the other hand, Crockett et al. (2007) simply employed a constant BC of -4.5 for the entire temperature range of WR stars, following Smith & Maeder (1989). More recent analyses of WR stars, however, seriously question the validity of this approach, as discussed below.

Hamann et al. (2006) and Sander et al. (2012) (hereafter, the Potsdam group) provide a homogeneous set of data on the properties of Galactic WR stars of different spectral types (WNL, WNE, WC, and WO). Fig. 1 shows the absolute narrow-band visual magnitudes M_v of the Galactic WR stars with known distances, as given by the Potsdam group. We note the strong temperature dependence of M_v : WR stars tend to be visually dimmer at higher temperatures. The corresponding BCs are presented in Fig. 2, for which the best linear fit is given by ²

$$BC = 22.053 - 5.306 \log T_\star. \quad (1)$$

To compute $BC = M_{\text{bol}} - M_V$, we adopt $M_v - M_V = 0.75$ to correct for the effect of strong emission lines on the visual broadband magnitude M_V (cf. Crockett et al. 2007). The BCs calculated by Maund et al. (2005) using the Potsdam WR grid are plotted in the same figure for comparison. Here again, the figure reveals that BCs for WR stars are a sensitive function of temperature, and that a more negative BC should be applied at a higher temperature. The synthetic spectra from the Potsdam WR models agree reasonably well with observations, confirming the temperature dependence of BCs.

To determine the implications of this finding for SN Ibc progenitors, we show a Hertzsprung-Russell (HR) diagram of evolutionary tracks of single massive helium stars of solar metallicity in Fig. 3. Our models were calculated with the hydrodynamic stellar-evolution code described in Yoon et al. (2010) using the WR mass-loss rates from Nugis & Lamers (2000). The figure shows that helium stars with initial masses higher than about

¹ Throughout this paper, M_v represents an absolute magnitude in the narrow visual-band ($3900 \lesssim \lambda \lesssim 4500$).

² In stellar evolution models, the hydrostatic surface temperature corresponds to the effective temperature at the surface boundary for which radial extension of the star due to optically thick WR winds is not considered. The empirical stellar temperatures T_\star in the Potsdam group data were estimated at large optical depth ($\tau_{\text{Ross}} = 20$) in the WR wind models (Sander et al. 2012) and thus nearly resemble the hydrostatic values. However, as the hydrostatic layers are not directly observable, the empirical T_\star rely on the adopted wind structure. For the stars with the strongest winds, we estimate a possible systematic uncertainty of up to 0.1 in $\log T_\star$ caused by this effect.

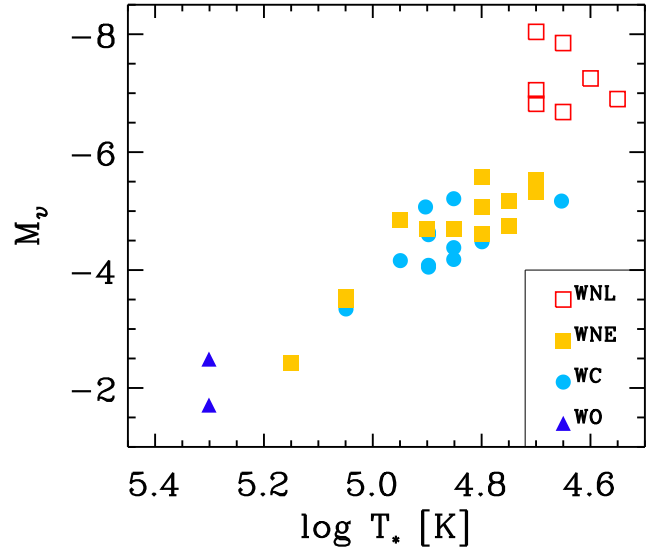


Fig. 1. Absolute visual magnitudes of Galactic Wolf-Rayet stars with known distances of different spectral types (WNL, WNE, WC and WO) as a function of surface temperatures. The data were taken from Hamann et al. (2006) and Sander et al. (2012).

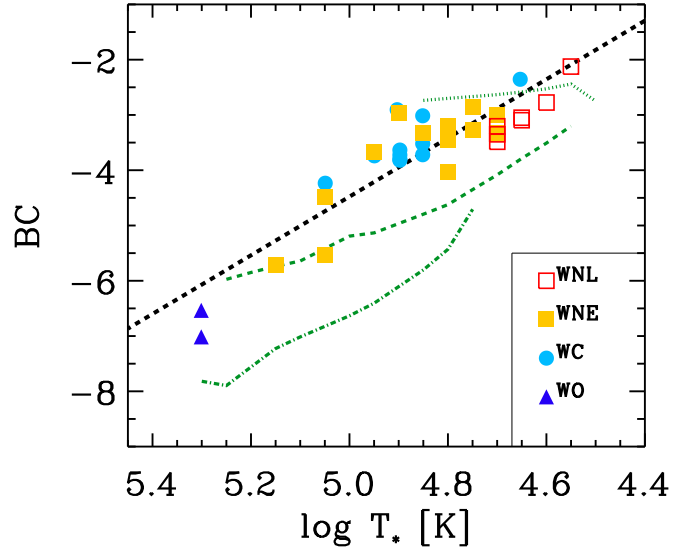


Fig. 2. Bolometric corrections (BCs) for Galactic WR stars, calculated from the data given in Fig. 1, as a function of surface temperatures. The thick dashed line gives the best fit to the data. The thin lines denote the BCs calculated by Maund et al. (2005) from the Potsdam WR-star synthetic spectra of Gräfener et al. (2002), for the minimum (dotted line), median (dashed line), and maximum (dot-dashed line) transformed radii R_t (see Maund et al. for details).

$15 M_\odot$ become gradually hotter. This is because they progressively lose their helium-rich envelopes in a stellar-wind, exposing the carbon-oxygen cores that gradually contract. The corresponding final masses are higher than about $9.0 M_\odot$ and the surface temperatures increase to $\log T_\star \simeq 5.3$ at the end of their evolution. We note that the recent single star-models of the Geneva group predict similar surface temperatures for WR stars of $\log L/L_\odot \gtrsim 5.3$ at the pre-supernova stage (Georgy et al.

2012). The question to be addressed now is which bolometric correction should be applied to such WR stars with $\log T_{\star} \gtrsim 5.3$.

Fig. 3 shows the well-known discrepancy between the predicted surface temperatures of WR stars and the observationally derived values: the helium-star models generally give higher temperatures than those of observed WR stars. Gräfenr et al. (2012) suggested that the observationally implied large radii of many Galactic WR stars are explained by envelope inflation caused by the iron opacity peak at $\log T \approx 5.18$ and the effect of density inhomogeneities (clumping) in the inflated layers. These inflated envelopes usually contain a strong density inversion, as is often observed in stellar models (Ishii et al. 1999; Petrovic et al. 2006). This density inversion is also observed in our helium-star models presented in Fig. 3, but the degree of inflation in our models is much weaker than in the Gräfenr et al. (2012) models because we do not consider the effect of clumping. Interestingly, given the key role of the iron peak, this inflation may no longer occur when the surface temperature of a star approaches or becomes hotter than the iron peak temperature ($\log T \approx 5.18$). Our helium-star models indeed show that the density inversion in the outermost layers, a sign of inflation caused by the iron peak, disappears when $\log T_{\star} \gtrsim 5.07$. This implies that, although massive WR stars have inflated envelopes for most of their lifetimes, the inflation disappears as they lose most of their helium envelopes and their cores become more compact during the late evolutionary stages. Gräfenr & Hamann (2005) showed that these compact stars form hot WR-type winds driven by the radiative force on the iron peak opacities. This may explain why the envelopes of these stars do not inflate and the positions of early-type WC and WO stars agree well with the model predictions, while WR stars of later spectral subtypes have much cooler temperatures.

Although we cannot directly apply the BCs of Fig. 2 to the stellar evolution models, we can draw the following conclusion: *massive WR stars experiencing strong mass-loss end their lives at their hottest point ($\log T_{\star} \approx 5.3$). Therefore, SN Ibc progenitors with final masses higher than about $9 M_{\odot}$ resemble the WO stars with $\log T_{\star} \approx 5.2$ and $M_{\nu} = -1.5 \dots -2.5$ (Fig. 1), rather than the majority of observed WR stars ($\log T_{\star} \lesssim 5$ and $M_{\nu} \lesssim -4$). They are relatively faint in optical bands compared to the majority of observed Galactic WR stars, and we cannot exclude massive WR stars of $\log L/L_{\odot} > 5.4$ as the progenitors of SNe 2000ds, 2004gt and 2002ap, in contrast to the previous conclusions of Maund & Smartt (2005), Maund et al. (2005), and Crockett et al. (2007).*

On the other hand, the helium envelopes in less-massive helium stars ($M = 8$ and $10 M_{\odot}$ Fig. 3) are not greatly stripped off and carbon is not enriched at the surface. These stars therefore rapidly expand during the late evolutionary stages beyond core helium-burning because of the mirror effect (cf. Kippenhahn & Weigert 1990). The surface temperature decreases from $\log T_{\star} \approx 5.2$ at core helium-exhaustion to $\log T_{\star} \approx 4.9$ at core oxygen-burning, accordingly. Although the bolometric luminosities of these SN Ibc progenitor models ($\log L/L_{\odot} \approx 5.2$) are lower than those of more massive ones ($\log L/L_{\odot} \gtrsim 5.4$), much lower temperatures at the pre-supernova stage imply that they should appear more luminous in optical bands. Given that WR stars with $\log T_{\star} < 5.0$ and $\log L/L_{\odot} < 5.3$ in the Potsdam sample have $M_{\nu} = -4 \dots -5$, similar M_{ν} s are expected for these SN Ibc progenitors.

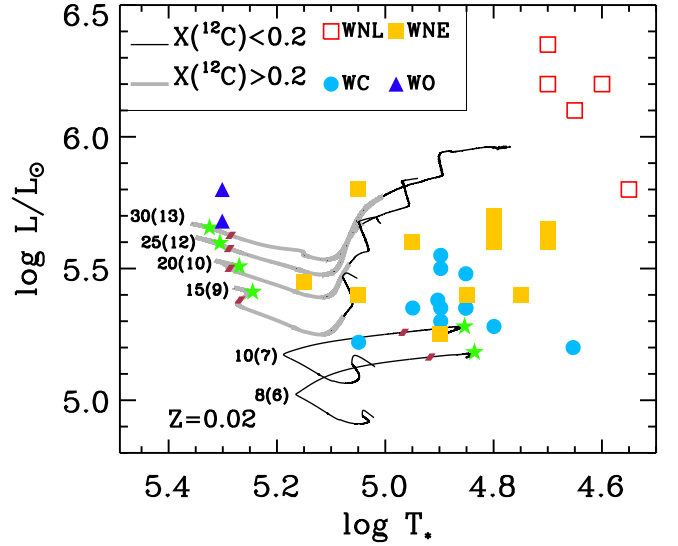


Fig. 3. Evolutionary tracks of pure helium-star models at solar metallicity in the HR diagram, for six different initial masses (8, 10, 15, 20, 25, and $30 M_{\odot}$), as indicated by the labels. The numbers in the parentheses denote the corresponding final masses. The positions where the surface mass-fraction of carbon is larger than 0.2 are marked by thick grey lines. The star symbol marks the end point of the evolution, which is the beginning of core oxygen-burning that occurs a few years before core collapse, for each evolutionary sequence, while the tilted rectangle denotes the position at 1000 yrs before the supernova explosion. The positions of Galactic WR stars with known distances given by Hamann et al. (2006) and Sander et al. (2012) are marked by open squares (WNL), filled squares (WNE), filled circles (WC), and triangles (WO).

3. Relatively low-mass helium stars in binary systems

Galactic WR stars have masses higher than about $8 M_{\odot}$ and many of them are thought to have originated from massive single stars through stellar-wind mass-loss. In binary systems, lower-mass helium stars can be produced via mass transfer. As discussed by Yoon et al. (2010), such relatively low-mass helium stars can retain a large amount of helium in the envelope and expand to a large radius during the late evolutionary stages beyond core helium exhaustion. The final radii of SN Ibc progenitors are hence systematically larger for lower masses.

Fig. 4 shows the evolutionary tracks of several helium stars produced in close binary systems taken from Yoon et al. (2010). Some of the helium stars in this figure (YWL9, YWL14 and YWL21) end their lives while they are filling their Roche-lobes during Case ABB or BB mass transfer (i.e., mass transfer from the He star during/after the carbon-oxygen core contraction phase; see Yoon et al. 2010 for more details). For comparison, the evolutionary track of a single, pure helium star of $M = 3 M_{\odot}$ is also presented in the figure. Since these relatively low-mass helium stars may not have optically thick winds, the black-body assumption is adopted as a rough approximation to calculate the corresponding visual magnitudes, which are shown in Fig. 4. This figure shows that helium stars of $M = 3 M_{\odot} - 5 M_{\odot}$ are visually very faint ($M_{\nu} > 1$) on the helium main-sequence. However, rapid expansion of the helium envelope during and after the carbon-burning phase suddenly makes these stars lumi-

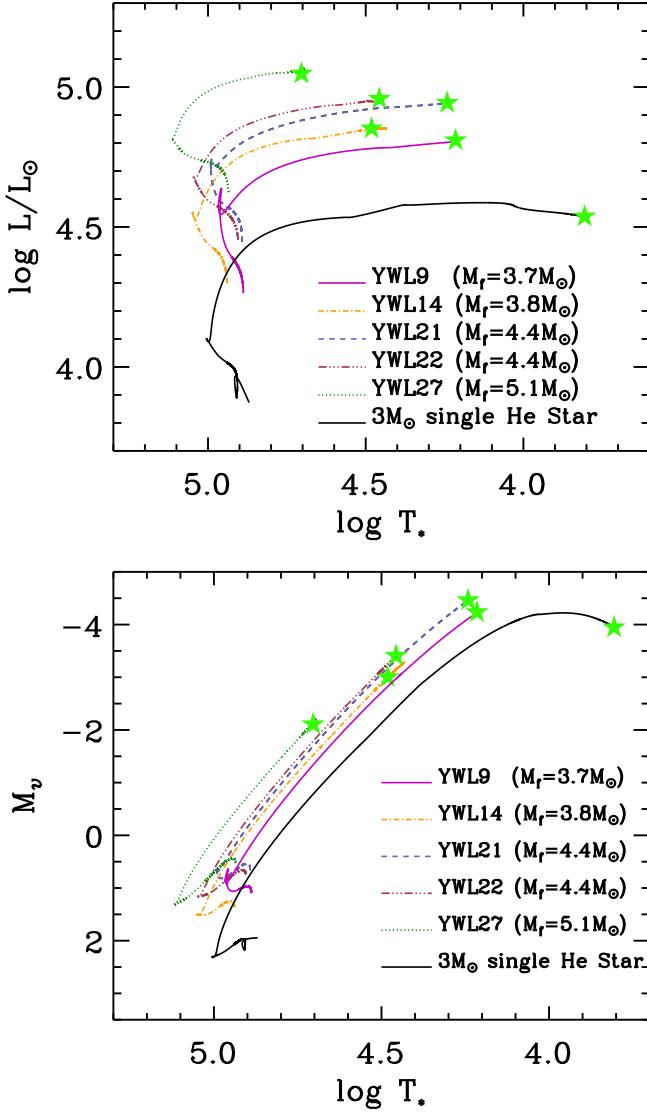


Fig. 4. *Upper panel:* Evolutionary tracks of helium stars produced in binary systems through Case AB or B mass transfer phase, and of a single helium star of $3 M_\odot$ (black solid line), at solar metallicity. The star symbol marks the end point of each evolutionary track, which is the core carbon burning phase for $3 M_\odot$ star and the oxygen burning phase for the others. The helium-star models in binary systems are taken from Yoon et al. (2010), and the evolutionary tracks are plotted only from the onset of core helium burning. The sequence number given for each track (except for the $3 M_\odot$ single helium star) denotes the model sequence number in Table 1 of Yoon et al. (2010). The final mass (M_f) for each model sequence is given in the parenthesis. *Lower panel:* Corresponding absolute narrow-band visual magnitudes calculated with the assumption of black-body radiation.

nous in the visual band shortly before their deaths. In particular, the surface temperature of $3 M_\odot$ helium star can decrease to $\log T_* = 3.8$ and it may be particularly luminous in the R band ($M_R \approx -5.5$).

The important implication of this result is that some relatively low-mass SN Ibc progenitors ($\sim 3 M_\odot$) are more luminous in either the visual band ($M_v \approx -4$) or other optical bands than much more massive SN Ibc progenitors with final masses

higher than about $9 M_\odot$, which should be as dim as $M_v \approx -1.5$ as discussed above (see also Fig. 1).

We note that not all SNe Ibc progenitors with final masses of $M < 5 M_\odot$ may be optically bright. Because they are likely to undergo mass transfer in a close binary system during the final evolutionary stages owing to the rapidly expanding envelopes, it is possible that some of them may lose most of their helium envelopes by the time of supernova explosion (if the orbital separation is sufficiently short; Pols & Dewi 2002; Dewi et al. 2002; Ivanova et al. 2003; Yoon et al. 2010). These relatively low-mass, helium-deficient stars may constitute the low-mass class of SN Ic progenitors (Pols & Dewi 2002; Yoon et al. 2010) and may explain the fast light-curve of SN 1994I (Nomoto et al. 1994). Such a SN Ic progenitor of the low-mass class has a surface temperature of $\log T_* > 5.0$ and a very faint optical luminosity ($M_v \gtrsim 1.0$). On the other hand, helium stars of about $2 M_\odot - 3 M_\odot$ can also be produced by a merging of a white dwarf and a helium star, in which case their surface temperatures may decrease below 10^4 K at the pre-supernova stage, which would appear to be optically bright single stars. Therefore, fairly diverse properties are expected for SN Ibc progenitor systems of this mass range.

4. Discussion

Our study refutes the widespread belief that more massive progenitors of SNe Ibc are more easily identifiable than less massive ones. In contrast, our analysis implies that massive SN Ibc progenitors with final masses $M \gtrsim 9 M_\odot$ and bolometric luminosities $\log L/L_\odot \gtrsim 5.4$ may be optically faint compared to relatively low-mass SN Ibc progenitors, depending on their mass-loss history.

The key factor that determines the brightness of a SN Ibc progenitor in optical bands is the mass of the helium envelope. If most of the helium envelope is lost via either stellar winds or binary interactions, the SN Ibc progenitor will be very hot, resulting in a low optical luminosity at the pre-supernova stage. This may be the case for the most massive WR stars as discussed in Sect. 2. If a fairly thick helium envelope can be retained in a SN Ibc progenitor, the expansion of the envelope that occurs shortly before the SN explosion makes the progenitor star fairly bright in optical bands. This case is mostly relevant for relatively low-mass helium stars produced in close binary systems (Sect. 3). Therefore, we suggest that SN Ib progenitors would be optically brighter – hence easier to detect – than SN Ic progenitors, in general.

We summarize in Table 1 our rough predictions for the visual magnitudes of SNe Ibc progenitors for different possible cases. A secure identification of a SN Ic progenitor would be challenging. A detection limit of $M_v \approx -1.5$ for SNe Ic of the high-mass class (i.e., $M_f \gtrsim 9 M_\odot$) and a much better detection limit is needed for SNe Ic of the low-mass class. Therefore, it is unsurprising that Crockett et al. (2007) could not find the progenitor star of SN Ic 2002ap even with the best detection limit achieved so far (i.e., $M_B \gtrsim -4.2$ and $M_R \gtrsim -5.1$). Although SNe Ib progenitors are predicted to be systematically more luminous than SNe Ic progenitors in optical bands, their visual luminosities would still be limited to $M_v \approx -5$ and a wide range of optical magnitudes are expected.

Given that many SNe Ibc are expected to occur in binary systems, another factor that should be considered in the search for SNe Ibc progenitors is the companion star. Even if a SN Ibc progenitor is optically faint, the companion star may be detectable. The binary star models indeed predict that a significant fraction

Table 1. Predicted visual magnitudes at the pre-supernova stage for different final masses of helium stars.

Final Mass	SN Type ^a	Helium envelope	Single/Binary	M_v
$M_f \gtrsim 9 M_\odot$	Type Ic	Stripped-off	Single or Binary	$M_v = -1.5 \cdots -2.5$
$6 \lesssim M_f \lesssim 8 M_\odot$	Type Ib	Retained	Single or Binary	$M_v = -4 \cdots -5$ ^b
$2 \lesssim M_f \lesssim 5 M_\odot$ ^c	Type Ib	Retained	Binary or merger remnant	$M_v = -2 \cdots -4$ ($M_R = -2.0 \cdots -5.5$)
$2 \lesssim M_f \lesssim 5 M_\odot$ ^c	Type Ic	Stripped-off	Binary	$M_v \gtrsim 1$

Notes. ^(a) SN Ic is assumed if the helium envelope is stripped off from the progenitor ($M_{\text{He}} \lesssim 0.5 M_\odot$) and SN Ib otherwise. However, this may also depend on the history of chemical mixing during the supernova explosion as shown by Dessart et al. (2012). ^(b) This estimate is based on the assumption that the helium stars of this mass range still have optically thick WR winds. If not, M_v is larger ($M_v \gtrsim -2$). ^(c) The lower limit of $2 M_\odot$ is an arbitrary choice, but SNe Ibc with $M < 2 M_\odot$ are likely to be very faint and difficult to discover.

of SNe Ibc progenitors have an O-type companion. However, not all of them are bright enough to be identified with the detection limits achieved in the previous observations. Our preliminary calculation indicates that only a small fraction (less than about 10%) of SNe Ibc progenitors have a luminous O star companion with $M_v < -4$.

5. Conclusion

Our study has shown that the masses of SNe Ibc progenitor stars are not linearly correlated with their optical brightness and that the evolution of the surface properties of massive helium stars during their final evolutionary stages should be carefully investigated. The non-detection of a SN Ibc progenitor even with a good detection limit does not necessarily imply that its progenitor is a relatively low-mass helium star, and vice versa. This should be properly taken into account in future observational efforts to directly identify SNe Ibc progenitors.

Acknowledgements. We are grateful to Georges Meynet, who refereed the paper, for his helpful comments. SCY would like to thank Norbert Langer for his support of this work.

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